

# A review of wildland fire spread modelling, 1990-present

## 2: Empirical and quasi-empirical models

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### Abstract

In recent years, advances in computational power and spatial data analysis (GIS, remote sensing, etc) have led to an increase in attempts to model the spread and behaviour of wildland fires across the landscape. This series of review papers endeavours to critically and comprehensively review all types of surface fire spread models developed since 1990. This paper reviews models of an empirical or quasi-empirical nature. These models are based solely on the statistical analysis of experimentally obtained data with or without some physical framework for the basis of the relations. Other papers in the series review models of a physical or quasi-physical nature, and mathematical analogues and simulation models. The main relations of empirical models are that of wind speed and fuel moisture content with rate of forward spread. Comparisons are made of the different functional relationships selected by various authors for these variables.

## Introduction

### History

An empirical model is one that is based upon observation and experiment and not on theory. Empiricism has formed the basis for much of the scientific and technological advances in recent centuries and generally provides the benchmark against which theory

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is tested. The study of fire and combustion in general was mainly an empirical endeavour, directed primarily toward application of combustion to industrial processes (for example, the industrial revolution of the late 1700s-1800s), until early in the previous century when the physical or theoretical approach had matured to the point of providing significant advances in understanding and prediction. The development of physical understanding of other forms of combustion (i.e. unintentional or uncontrolled fire) in general and wildland fires in particular, did not occur, however, until only very recently (in the last few decades) (Sullivan, 2007).

While there had always been a great general interest in unintentional fire in urban settings (Williams, 1982), for instance, the Great Fire of London in 1666, or the Chicago Fire on October 1871—prevention, control, prediction—unintentional fire in wildlands received much less attention, mainly due to the relatively little impact such fires have on the general populace. The study of the behaviour of fires in wildland regions has traditionally been driven by the needs of those practitioners involved in wildland resource management—foresters for the most part—for whom understanding this natural phenomenon was critical to the success of their work.

Despite the fact that practically no region of the world (except for Antarctica) is free from such fires, much of the work in this field was galvanised in the United States following the devastating 1910 fires in the mid-west (Pyne, 2001), where workers such as Hawley (1926) and Gisborne (1927, 1929) pioneered the notion that understanding of the phenomenon of wildland fire and the prediction of the danger posed by a fire could be gained through measurement and observation and theoretical considerations of the factors that might influence such fires. Curry and Fons (1938, 1940), and Fons (1946) brought a rigorous physical approach to the measurement and modelling of the behaviour of wildland fires that set the benchmark for wildland fire research for decades following.

In addition to the work conducted in the US, through the Federal US Forest Service and State agencies, other countries became increasingly involved in wildland fire research, primarily through their forest services—the Canadian Forest Service, the Commonwealth Forestry and Timber Bureau (later absorbed into the Commonwealth Scientific and Industrial Research Organisation (CSIRO)) in conjunction with various state authorities in Australia—although many other countries such as South Africa, Spain, Russia, France, Portugal to name a few, have also had significant impact on wildland fire research.

Since the early 1990s, European Union countries have committed significant funds towards wildland fire research, resulting in a boom period for this research in mainly Mediterranean countries and a major shift in focus away from the pioneering three (US, Canada and Australia).

During the past two decades, the direction of much of the wildland fire research has been toward the use of fire as a resource management tool in the form of hazard reduction burning or the study of ecological effects of fire (e.g. Gill et al. (1981); Goldammer and Jenkins (1990); Abbot and Burrows (2003)).

## **Empirical modelling**

The focus of empirical modelling of wildland fire in the past has been on the determination of the key characteristics used to describe the behaviour of the fire. These generally have

been the rate of forward spread (ROS) of the head fire (that portion of the fire perimeter being blown downwind and normally of much greater intensity than the rest of the fire perimeter), the height of the flames, the angle of the flames, and the depth of flames at the head, although other characteristics such as rate of perimeter or area increase may also be of some interest.

While observations of wildfires or fires lit intentionally for other purposes (such as hazard reduction or prescribed fires) have been used in the development of empirical models of fire behaviour, the predominant method has been the lighting of ‘experimental’ fires—fires whose only purpose is that of an experimental nature. This method can be divided into four parts. Firstly, the characterisation and quantification of the fuel and terrain in which the fire will lit (the slowly varying variables, which has included fuel load, fuel height, moisture content, bulk density, combustion characteristics, slope, etc.). Secondly, the observation and measurement of the atmospheric environment (the quickly varying variables, wind speed and direction, air temperature, relative humidity, etc.). Thirdly, the lighting, observation and measurement of the fire itself (its speed, spread, flame geometry, combustion rate, combustion residues, smoke, etc.). Fourthly, the statistical correlation between any and all of the measured quantities in order to produce the model of fire behaviour. Many workers have chosen to limit or control the possible natural variation in many quantities by conducting experimental fires in laboratory conditions which aids in the analysis of such fires.

The primary use of such models has been to estimate the likely spread in the direction of the wind (and potential for danger to firefighter safety) for suppression planning purposes, much of which has traditionally been conducted in the form of simple ‘back of the envelope’ calculations for plotting on a wall map. Due to this simple need, empirical fire spread models have traditionally been one dimensional models in which the independent variable that is predicted is the rate of forward spread of the head of the fire in the direction of the wind. The rather pragmatic nature of these models, their relatively straightforward implementation, their direct relation to the behaviour of real fires, and, perhaps most importantly, their development by for the most part by forestry agencies for their own immediate use, have meant that empirical fire spread models have gained acceptance with wildland fire authorities around the world and to varying degrees form the basis for all operational fire behaviour models in use today.

## Operational models

In the United States, the quasi-empirical model of Rothermel (1972) forms the basis of the National Fire Danger Rating System (Deeming et al., 1977; Burgan, 1988) and the fire behaviour prediction tool BEHAVE (Andrews, 1986). This model is based on a heat balance model first proposed by Fransden (1971) and utilised data obtained from wind tunnel experiments in artificial fuel beds of varying characteristics and from Australian field experiments of grassfires in a range of wind speed conditions to correlate fire behaviour with measured input variables. The model of Rothermel (1972) and associated systems have been introduced to a number of countries, particularly Mediterranean Europe.

In Australia, the predominant operational fire spread prediction systems have been the McArthur Grassland (McArthur, 1965, 1966) and Forest (McArthur, 1967) Fire Danger Rating Systems (FDRS), and the Forest Fire Behaviour Tables for Western Australia

(commonly called the Red Book) (Sneeuwjagt and Peet, 1985), based on the work of Peet (1965). Both McArthur's systems and the Red Book are purely empirical correlations of observed fire behaviour and measured fuel and environmental variables from mainly field experimental fires augmented by well-documented wildfires. More recently, the CSIRO Grassland Fire Spread Meter (GSFM) (CSIRO, 1997; Cheney and Sullivan, 1997) based on the empirical modelling of Cheney et al. (1998) has replaced the McArthur Grassland FDRS as the preferred tool for predicting fire behaviour in grasslands. This, too, is based on field experimentation and documented wildfire observations.

In Canada, the quasi-empirical Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992) forms part of the Canadian Forest Fire Danger Rating System (CFFDRS) and is the culmination of 60 years of research effort in fuel moisture and fire behaviour (Van Wagner, 1998; Taylor and Alexander, 2006). Almost 500 fires were used in the construction of the FBP system, of which approximately 400 were field experiments, the remainder well-documented observations of prescribed and wild fires. The CFFDRS has been introduced and implemented in a number of countries, including New Zealand, Mexico and several countries of south-east Asia.

The main characteristic of all but the CSIRO GSFM is that these systems were based primarily on small (<1 ha) experimental or laboratory fires and augmented with wildfire observations<sup>3</sup>. The series of experiments upon which the CSIRO GSFM was based (Cheney et al., 1993) was the first to use experimental burning plots of which the smallest was 1 ha (See review of this model below).

## Background

This series of review papers endeavours to comprehensively and critically review the extensive range of modelling work that has been conducted in recent years. The range of methods that have been undertaken over the years represents a continuous spectrum of possible modelling (Karplus, 1977), ranging from the purely physical (those that are based on fundamental understanding of the physics and chemistry involved in the behaviour of a wildland fire) through to the purely empirical (those that have been based on phenomenological description or statistical regression of fire behaviour). In between is a continuous meld of approaches from one end of the spectrum or the other. Weber (1991), in his comprehensive review of physical wildland fire modelling, proposed a system by which models were described as physical, empirical or statistical, depending on whether they accounted for different modes of heat transfer, made no distinction between different heat transfer modes, or involved no physics at all. Pastor et al. (2003) proposed model descriptions of theoretical, empirical and semi-empirical, again depending on whether the model was based on purely physical understanding, of a statistical nature with no physical understanding, or a combination. Grishin (1997) divided models into two classes, deterministic or stochastic-statistical. However, these schemes are rather limited given the combination of possible approaches, and, given that describing a model as semi-empirical or semi-physical is a 'glass half-full or half-empty' subjective issue, a more comprehensive and complete convention was required.

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<sup>3</sup>Another interesting characteristic is that the CSIRO GSFM model was the only one published in a peer-reviewed journal; all the others were published as technical reports by the associated organisations.

Thus, this review series is divided into three broad categories: Physical and quasi-physical models; Empirical and quasi-empirical models; and Simulation and Mathematical analogous models. In this context, a physical model is one that attempts to represent both the physics and chemistry of fire spread; a quasi-physical model attempts to represent only the physics. An empirical model is one that contains no physical basis at all (generally only statistical in nature), a quasi-empirical model is one that uses some form of physical framework upon which to base the statistical modelling chosen. Empirical models are further subdivided into field-based and laboratory-based. Simulation models are those that implement the preceding types of models in a simulation rather than modelling context. Mathematical analogous models are those that utilise a mathematical precept rather than a physical one for the modelling of the spread of wildland fire.

Since 1990 there has been rapid development in the field of spatial data analysis, e.g. geographic information systems and remote sensing. Following this, and the fact that there has not been a comprehensive critical review of fire behaviour modelling since Weber (1991), I have limited this review to works published since 1990. However, as much of the work that will be discussed derives or continues from work carried out prior to 1990, such work will be included much less comprehensively in order to provide context.

## Previous reviews

Many of the reviews that have been published in recent years have been for audiences other than wildland fire researchers and conducted by people without an established background in the field. Indeed, many of the reviews read like purchase notes by people shopping around for the best fire spread model to implement in their part of the world for their particular purpose. Recent reviews (e.g. Perry (1998); Pastor et al. (2003); etc), while endeavouring to be comprehensive, have offered only superficial and cursory inspections of the models presented. Morvan et al. (2004) take a different line by analysing a much broader spectrum of models in some detail and conclude that no single approach is going to be suitable for all purposes.

While the recent reviews provide an overview of the models and approaches that have been undertaken around the world, mention must be made of significant reviews published much earlier that discussed the processes in wildland fire propagation themselves. Foremost is the work of Williams (1982) which comprehensively covers the phenomenology of both wildland and urban fire, the physics and chemistry of combustion, and is recommended reading for the beginner. The earlier work of Emmons (1963, 1966) and Lee (1972) provides a sound background on the advances made during the post-war era. Grishin (1997) provides an extensive review of the work conducted in Russia in the 1970s, 80s and 90s. Chandler et al. (1983) and Pyne et al. (1996) provide a useful review of the forestry approach to wildland fire research, understanding and practice.

The first paper in this series discussed those models based upon the fundamental principles of the physics and chemistry of wildland fire behaviour. This particular paper will discuss those models based directly upon only statistical analysis of fire behaviour observations or models that utilise some form of physical framework upon which the statistical analysis of observations have been based. In this paper, particular distinction is made between observations of the behaviour of fires in the strictly controlled and artificial conditions of the laboratory and those observed in the field under more naturally occurring conditions.

The last paper in the series will focus upon models concerned only with the simulation of fire spread over the landscape and models that utilise mathematical conceits analogous to fire spread but which have no real-world connection to fire.

## Empirical models

The following sections identify and discuss those empirical and quasi-empirical surface-only fire spread models that appeared in the literature since 1990. It is interesting to note the observation of Catchpole (2000) that the majority of new models that have been developed in recent years have been the result of efforts to initially develop and validate local fuel models required for the implementation of the BEHAVE (based on Rothermel) fire behaviour prediction system. Many researchers obviously felt that it was far easier to start from scratch with a purpose built model than to try to retrofit their local conditions into an existing model. Table 1 summarises the empirical models discussed in this review.

Due to the varied nature of the empirical models presented here, including the fuels and weather conditions under which the data for the construction of the models were collected, the size and number of experimental fires and purposes for which the models were developed, it is difficult to compare them side by side. One possible method is the relationship between rate of forward spread (ROS) and wind speed. Wind speed is widely accepted as being the dominant variable determining the forward speed of a fire front. The reasons for this are cause for significant debate, ranging from the reduction in angle of separation of flame to unburnt fuel to increased turbulent mixing of combustants. Regardless of the mechanics of the process, the empirical approach to modelling fire spread must cater for this process and is manifested in the functional form chosen to represent it. Fuel moisture content (FMC) is also a key variable in determining rate of spread and this is also discussed. Fire spread models for fuel layers other than surface fuels, such as crown fires or ground fires, are not covered.

### Canadian Forest Service (CFS) - Acceleration (1991)

While the Canadian Forest Service (CFS-accel) work (McAlpine and Wakimoto, 1991) is not a model of fire spread as such, it does address a major concern of fire spread, namely the acceleration in rate of fire spread from initiation. The assumption is that a fire will attain an equilibrium rate of spread for the prevailing conditions (the prediction of which is the primary aim of all fire spread prediction systems discussed here). The form of the function for the time to reach this equilibrium ROS is assumed to be exponential based on models proposed by Cheney (1981) and Van Wagner (1985) (as cited by McAlpine and Wakimoto (1991)).

29 experimental fires were conducted in a wind tunnel with a fuel bed 6.15 m long by 0.915 m wide consisting of *Pinus ponderosa* needles or excelsior<sup>4</sup> of varying fuel load and bulk density. Four wind speeds (0, 0.44, 1.33 and 2.22 m s<sup>-1</sup>) measured at mid-flame height were used. Temperature and relative humidity were held constant at 26.7°C and 80%.

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<sup>4</sup>Excelsior is wood shavings cut into long thin strands

Equilibrium ROS was assumed to occur after 2.0 m of forward spread and determined using linear regression of averaged fire location and time measurements.

Acceleration was modelled as an allometric (power law) function asymptoting to the equilibrium ROS with two coefficients, one based on the equilibrium ROS (which eliminated differences in fuel properties and integrated all other burning condition variables) and the other on the wind speed. The model was found to well represent the laboratory data but observations of elapsed time to equilibrium ROS did not coincide with point source field observations of other authors which were much greater and also dependent on wind speed.

## **CALM Spinifex (1991)**

The Western Australia Department of Conservation and Land Management (CALM) Spinifex model (Burrows et al., 1991) was developed from 41 experimental fires conducted in predominantly spinifex (*Triodia basedowii* and *Plectrachne schinzii*) fuels on relatively flat sand plains. These fires were lit using drip torches to create lines of fire up to 200 m long perpendicular to the wind direction. Fuel particle dimension and arrangement were measured for individual clumps; fuel distribution, quantity and moisture content were measured using line transect methods. Bare ground between clumps was also measured. Wind speed and direction, air temperature and relative humidity were measured at 10-min intervals. Wind speed ranged over 1.11 - 10 m s<sup>-1</sup> and FMC over 12-31%. Fire spread was measured using metal markers placed near the flame front at intervals of 1-4 mins and later surveyed. Fires were allowed to spread until they self-extinguished. The range of ROS was 0-1.53 m s<sup>-1</sup>. Data gathered were analysed using multiple linear regression techniques.

Burrows et al. (1991) found that above a threshold wind speed zone (3.33-4.72 m s<sup>-1</sup>), in which flames are tilted sufficiently to bridge the gap between hummocks (Bradstock and Gill, 1993; Gill et al., 1995), the ROS varied with the square of the wind speed ( $R^2 = 0.85$ ). Below the threshold wind speed zone, which depends on the percent cover of fuel (ratio of percentage of area covered by hummocks to bare ground), the fire does not spread. The higher the percent cover, the lower the threshold wind speed required. A lesser, negative, linear correlation was determined with FMC. Percent cover and air temperature were also found to influence the ROS but much less than either wind or FMC. Fuel load and other fuel characteristics were found not to be important.

## **Canadian Forest Fire Behaviour Prediction (CFBP) System (1992)**

The Canadian Forest Fire Behaviour Prediction (CFBP) System is a component of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al., 1991), which also incorporates the Canadian Forest Fire Weather Index (CFFWI) System. The CFFDRS is the result of continuing research into forest fire behaviour since the mid-1920s and has undergone several incarnations in that time. The current CFFDRS system came into being in the late 1960s in the form of a modular structure. The first major component to be completed was the CFFWI in 1971, which provided a relative measure of fuel moisture and fire behaviour potential for a standard fuel type, and has been revised several times since

its introduction (Van Wagner, 1987). While there have been several interim editions of the CFBP, the first of which appeared in 1984 (Lawson et al., 1985), it was not until 1992 that a final version of the prediction system was released (Forestry Canada Fire Danger Group, 1992; Taylor and Alexander, 2006) and thus is covered in this review.

The CFBP system, following on from the long-established Canadian approach to studying wildland fire, is based on the combined observations of nearly 500 experimental, prescribed and wild fires in 16 discrete fuel types covering 5 major groups: coniferous, deciduous, mixed wood, slash and grass fuels. The experimental work on which the system is based was conducted by individual researchers working in specific fuel types and locales across the country using a variety of methods and published in a variety of places (initially including the 1966 work of McArthur in Australian grasslands, later replaced by the data of Cheney et al. (1993) (Forestry Canada Fire Danger Group, 1992)). Alexander et al. (1991) provides an overview of the methods used since the 1960s to obtain the dataset from the CFBP was derived, but which, due to a number of factors (including technological improvements) evolved over the years. The result is a system constructed by a small group of dedicated researchers over a period of 20 years that has broad applicability to a wide range of fuels and climates.

Experimental burn plots varied in size from 0.1 ha up to 3 ha (Alexander et al., 1991), with the majority being less than 1 ha. Ignition methods included both point ignitions as well as line-ignitions. Wind speed unaffected by the fire was measured at 10-m in the open (or converted a 10-m in the open equivalent). Experiments were usually conducted in the late afternoon in order to attain maximum burning conditions for the day. ROS was normally measured by visual observations of fire passage over predetermined distances. For point ignition experiments, metal tags were placed at the head and flanks of the fire and surveyed afterwards.

The final version of the CFBP system works in conjunction with the CFWI system to determine an Initial Spread Index (ISI) for the standard fuel type (pine forest) and based solely on fine FMC and wind speed. The functions chosen for the effect of wind speed and fine FMC on the ISI are exponential (exponent 0.05039) for wind, and a complicated mix of exponential and power law (exponents -0.1386 and 5.31 respectively) for FMC (Van Wagner, 1987). No quantification of performance of these functions is given.

To predict ROS, the ISI is modified by a Build-up Index (BUI), which is a fuel-specific fuel consumption factor that includes fuel moisture. Predicted ROS is the headfire ROS on level terrain under equilibrium conditions, thereby implicitly including effects of acceleration and crowning (Forestry Canada Fire Danger Group, 1992). The effect of slope (Van Wagner, 1977b) and crown fire transition effects (Van Wagner, 1977a) then modify the basic ROS. Recent work of the International Crown Fire Modelling Experiment (Stocks et al., 2004) has investigated the behaviour of fully-developed crown fires (which is not covered in this review as it is outside the scope of surface fire spread).

## **Button (1995)**

Marsden-Smedley and Catchpole (1995b) presented a model for the prediction of ROS and flame height of fires in Tasmanian buttongrass moorlands, described as largely treeless communities dominated by sedges and low heaths (Marsden-Smedley and Catchpole,



1995a). The behaviour of 64 fires (of which 44 were experimental fires, 4 test fires, 11 fuel reduction fires and 5 wildfires) at 12 sites was measured. Experimental burns were conducted on blocks of either 0.25 or 1.0 ha with ignition line lengths of 50 or 100 m respectively under a limited range of weather conditions. ROS was measured by either using metal tags thrown at different times or by timing the passage of flames past pre-measured locations. For experimental fires, wind speed and direction, temperature and relative humidity were measured at 10 m, and wind speed only at 1.7 m above ground level, all averaged over 1-3 min periods. Meteorological data for non-experimental fires were collected using handheld sensors at 1.7 m. Data ranged from 0.19 - 10 m s<sup>-1</sup> for wind speed and 8.2-96% for FMC, and 0 - 0.92 m s<sup>-1</sup> for ROS.

Marsden-Smedley and Catchpole (1995b) found surface wind speed, dead FMC and fuel age (time since last fire) to be the key variables affecting ROS, with wind being the dominant factor. Age and FMC each accounted for 15 to 20% of the observed variation in ROS. A power law with an exponent of 1.312 was used to describe the effect of wind, whereas both the FMC and fuel age were modelled as exponential functions (FMC decreasing, age increasing to a maximum at about 40 years). Rates of spread of the back and flank of the fires were found to be approximately 10% and 40% of the head ROS, respectively.

## CALM Mallee (1997)

McCaw (1997) conducted a large-scale field experiment in *Eucalyptus tetragona* mallee-heath community in south-west Western Australia. Shrubs < 1.0 m tall comprised more than half the plant species present. Burn plots 200 m × 200 m were established in 20-year-old fuel in flat terrain. A semi-permanent meteorological site was set up 500 m from the experimental plots recording 30 min averages of temperature and relative humidity at 1.5 m and wind speed and direction at 2 m. During each experiment, mean wind speed and direction at a location up to 250 m upwind of the plot were measured at heights of 2 m and 10 m at 30 s intervals. FMC was measured using 5 samples of four fuel components (3 dead and 1 live) collected post-fire within 30 min of ignition. Wind speed at 10 m in open ranged from 1.5-6.9 m s<sup>-1</sup>, FMC 4-32%. Experimental fires were ignited using a vehicle-mounted flame thrower to establish a line perpendicular to the prevailing wind up to 200 m long. Fire spread was measured using buried electronic timers (placed on a 24-point grid) equipped with a fusible link that melted on exposure to flames. ROS ranged 0.13-0.68 m s<sup>-1</sup>.

Isopleths representing the position of the fire front at successive time intervals were fitted to the grid of timer data for each plot using a contouring routine based on a distance-weighted least squares algorithm. ROS up to 0.67 m/s and fireline intensities up to 14 MW/m were recorded. Fires were found to spread freely when the FMC of the dead shallow litter layer beneath the low shrubs was < 8%. Forward ROS was modelled as a function of the wind speed in the open at 2 m and FMC of the deep litter layer. These accounted for 84% of the variation in ROS. A power function (exponent 1.05) and an exponential (coefficient -0.11) were chosen to describe wind (measured at 2 m) and FMC influences respectively (McCaw, 1997, page 142). Good agreement between the model and observations of rate of spread of a limited number of prescribed and wild fires (up to ROS = 1.1 m/s), although observed ROS of a wildfire burning under extreme fire danger conditions was over-predicted by 30%.

## CSIRO Grass (1997)

The CSIRO Grassland Fire Spread Meter (CSIRO, 1997) is a cardboard circular slide rule that encapsulates the algorithms developed by Cheney et al. (1998) for fire spread in natural, grazed and eaten-out grassland pastures. These algorithms are based primarily on the results of experiments conducted in annual grasses of the Northern Territory with the aim of determining the relative importance of fuel characteristics on rate of forward spread of large unconstrained fires, particularly fuel load (Cheney et al., 1993), augmented by large experimental fires conducted in open woodland (Cheney and Gould, 1995) and detailed observations of 20 wildfires. 121 experimental fires were carried out on a flood plain in a range of fuel treatments under a variety of weather conditions (Cheney et al., 1993; Cheney and Gould, 1995) in prepared blocks ranging in size from  $100 \times 100$  m to  $200 \times 300$  m. These fires were predominantly lit from lines ranging in length from 30 to 175 m, although there were also a number of point ignitions, and allowed to burn freely. The range of fuel treatments included mowing and removing cuttings, mowing and retaining cuttings, or leaving the grass in its natural state. Two distinct grass species (*Eriachne burkittii* and *Themeda australis*), of different height, bulk density and fineness were present.

Fuel characteristics (height, load, bulk density, etc.) were measured on four transects through each plot approximately every 25 m. In addition to remote standard 10 m and 2 m meteorological stations, the wind speed at 2 m was measured at the corner of each plot and averaged for each ROS interval. FMC samples were taken before and after each fire. ROS and flame depth were measured from a series of rectified time-stamped oblique aerial photographs of each fire. Wind speed ranged from  $2.9 - 7.1 \text{ m s}^{-1}$ , FMC 2.7-12.1%, and ROS  $0.29\text{-}2.07 \text{ m s}^{-1}$ .

Cheney and Gould (1995) found the growth of the fires to be related to wind speed and the width of the head fire normal to the wind direction. They found that the width of the fire required to achieve the potential quasi-steady ROS for the prevailing conditions increased with increasing wind speed, and the time to reach this quasi-steady ROS was highly variable. ROS was found to depend on the initial growth of the fire, the pasture type (natural, grazed or eaten-out), wind speed and live and dead FMC. Utilising the notion of potential quasi-steady ROS and a minimum threshold wind speed for continuous forward spread, Cheney et al. (1998) developed a model of fire spread assuming a width necessary to reach the potential ROS. This model uses wind speed, dead FMC and degree of curing to predict the potential (i.e. unrestricted) ROS for the prevailing conditions. Above a threshold of  $5 \text{ km h}^{-1}$  the ROS is assumed to have a power function (with an exponent less than 1 (0.844)) relation with the wind speed. This wind speed function is similar to that proposed by Thomas and Pickard (1961), in which a power function with exponent of just less than 1 was found. Less than the threshold, the ROS is linear with wind speed and dominated by dead FMC.

## Heath (1998)

A cooperative research effort from a number of Australasian organisations, Heath (Catchpole et al., 1998a) utilises observations of 133 fires (comprising a mix of experimental (95), prescribed

(22) and wild (16) fires) conducted in mixed heathland (heath and shrub) fuels. This includes 48 experiments conducted by Marsden-Smedley and Catchpole (1995b) in button-grass. Only experimental and prescribed fires were used in model development; wildfire observations were used for validation.

In mixed heathland (comprising heath, scrub and gorse in New Zealand and mixed species including Banksia, Hakea and Allocasuarina in Australia), fuel age ranged from 5-25 years. Fires were lit as lines of unstated length on slopes  $< 5^\circ$ . Due to the disparate nature of the researchers involved, methods for measuring variables varied from experiment to experiment. Wind speed was generally measured by handheld anemometry at 2 m at 20 s intervals and averaged over the life of the fire. Wind speed ranged from 0.11-10.1  $\text{m s}^{-1}$  and ROS 0.01-1.00  $\text{m s}^{-1}$ . Fuel load does not appear to have been measured but fuel height was. FMC was measured in some cases and modelled in others using pre-established functions based on air temperature and relative humidity.

Wind speed was found to account for 53% of the variation in ROS. Aerial dead fuel (i.e. those fuels not in contact with the ground) FMC was found not to be significant. Fuel height was highly significant and with wind accounted for 70% of the variation in ROS. A power function of wind speed (exponent 1.21) was used to describe this variation. A power function was also used for fuel height (exponent 0.54).

The model was found to perform reasonably well for the selection of wildfires, considering the paucity of available data and necessary assumptions about the involved fuel characteristics (fuel height, moisture etc.) but could be improved with more variables. The wind power function does fail for zero wind but was found to better fit the data than an exponential growth function.

## PortShrub (2001)

Fernandes (2001, 1998) presented a model developed from field experiments and observations of prescribed burns conducted in four different types of shrub in flat terrain of Portugal. He found that Rothermel (1972) did not predict observed ROS well. 29 fires were conducted on flat ( $< 3^\circ$  slope) in gorse, low heath, tall heath and tall heath/tree mix. Fine aerial live and dead FMC was sampled prior to each burn. Meteorological variables (wind speed, air temperature, relative humidity) were measured at 2 m in the open using either a fixed weather station placed near the burn plot or upwind with handheld instruments. Fires were lit as lines of length 10 m in experimental fires and 100 m in prescribed burns. ROS was measured by recording time of arrival of the head fire at reference locations. Wind speed ranged 0.28-7.5  $\text{m s}^{-1}$ , FMC 10-40% and ROS 0.01-0.33  $\text{m s}^{-1}$ .

ROS was significantly correlated with wind speed (1% level) and less so with RH, temperature, and aerial dead FMC (5%). Other fuel characteristics were also found to affect ROS but were strongly intercorrelated and thus could not be separated, however, preference was given to fuel height. The initial model found a power law (exponent 1.034) for wind speed. However, as the model predicted no ROS in zero wind, an exponential function (coefficient 0.092) was subsequently incorporated. The final model, with an exponential decay function for dead FMC (coefficient -0.067) and power function (exponent 0.932) for fuel height, improved the overall performance of the model ( $R^2 = 0.91$ ). The model was

also found to predict well the data sets of other authors and be in close agreement with other field studies (e.g. Marsden-Smedley and Catchpole (1995b); Cheney et al. (1998); Catchpole et al. (1998a)).

## CALM Jarrah I (1999)

Burrows (1999a, 1994) conducted a series of 144 laboratory experiments (54 wind-driven, 6 no wind, 13 backing, 34 with slope, 15 point ignition) using fallen leaves and twigs ( $<6$  mm) placed on a 4 m long by 2 m wide table set in a large shed. Wind was supplied by four domestic fans calibrated to give a desired wind speed over the fuel bed. FMC was varied by uncontrolled ambient conditions and wetting prior to burning. It ranged from 3 to 14%. Fires were lit along the 2 m upwind edge using cotton wick soaked in methylated spirits and allowed to burn for 50 cm before measurements commenced. ROS was measured by recording time taken to reach end of fuel bed. Wind was varied from 0.0 to 2.1 m s<sup>-1</sup> with mean 1.06 m s<sup>-1</sup>. ROS ranged 0.002-0.075 m s<sup>-1</sup>.

In wind-driven fires, no relationship between fuel load and forward ROS was found. Most variation in ROS was due to wind speed (correlation coefficient 0.94). ROS was negatively related to FMC (correlation coefficient -0.31). Backing ROS was found to be directly related to fuel load.

At wind speeds  $< 0.83$  m s<sup>-1</sup>, ROS was relatively insensitive to wind. Above this value, ROS was found to vary linearly with wind speed. However, a power function (exponent 2.22) was used to model wind speed effect on ROS. An inverse linear function was used for FMC. This model was found to underspecify ROS  $> 3.33$  m s<sup>-1</sup> with an error variance that increased with ROS.

## CALM Jarrah II (1999)

Burrows (1999b, 1994) studied four series of fire behaviour data obtained from field experiments and fuel reduction burns on flat to gently sloping terrain in Jarrah (*Eucalyptus marginata*) forest in south-west Western Australia to test Jarrah I and other models for forest fire spread. Fuel was characterised by a layer of dead leaves, twigs, bark and floral parts on the forest floor with low ( $<0.5$  m, 30% cover) understorey of live and suspended vegetation. Plots were 100 m wide  $\times$  200 m long. 56 of 66 total plots were lit from lines of 50-100 m length, the remainder being point ignitions.

Historical (pre-fire) weather data (including rainfall, temperature, relative humidity, wind speed and direction at 2 hourly intervals) were obtained from nearby permanent weather stations. During each experiment a portable weather station approximately 50 m from the fire recorded wind speed at 1.5 m and 10 m and temperature and relative humidity at 1.5 m at 5 minute averages. FMC was measured at the time of ignition. Wind speed at 10 m in the open ranged 0.72-3.33 m s<sup>-1</sup> and FMC 3-18.6%.

ROS was measured by recording the time of arrival at a grid of predetermined locations, along with other fire characteristics, after first allowing the fire to spread 20 - 40 m ( $\simeq$  15 min) in order for it to attain a quasi-steady ROS for the prevailing conditions. The

position of the flames in relation to the grid was mapped at 5 min intervals. ROS ranged 0.003-0.28 m s<sup>-1</sup>.

Unlike the laboratory findings (Burrows, 1999a), Burrows here found a non-linear relation between wind speed and ROS. A power function (exponent 2.674) was selected. FMC was determined to also be a power function (exponent -1.495). Like the laboratory findings, fuel load was not found to correlate with ROS. The model was found to underpredict ROS of large wildfires burning under severe conditions.

## Gorse (2002)

Baeza et al. (2002) conducted field experiments during spring and autumn in gorse shrublands of eastern Spain with the aim of developing a prescribed burning guide. Fuels were 3, 9 and 12 years old and were replicated 3 times resulting in a total of 9 fires. Plots were 33 m × 33 m and were burnt under low (< 1.39 m s<sup>-1</sup> at 2 m) wind, utilising headfire spread for the 3-year-old fuel and backing fires for the other two age classes. Meteorological data was recorded at 2 m at 15 min intervals. Fuel characteristics were recorded along 5 parallel transects 5 m in length. FMC was measured from 10 samples of the most abundant species collected prior to ignition and ranged from 22-85%, presumably including both live and dead fuels<sup>5</sup>. Ignition technique is not specified. ROS was measured by recording the time to travel a fixed distance within the plot and ranged 0.004-0.039 m s<sup>-1</sup>.

It was found that FMC was the dominant factor affecting ROS in a linear manner (coefficient 0.487). The combination of heading and backing propagation negated any consistent effect of wind speed on ROS.

## PortPinas (2002)

Fernandes et al. (2002) developed a model for the behaviour of fires in maritime pine (*Pinus pinaster* stands in northern Portugal under a range of fire weather conditions that occur outside the wildfire season for the purpose of improving the understanding of prescribed fire for hazard reduction. Six study sites in mountainous terrain with forests founded by plantation or regeneration following fire events and aged 14 to 41 years were established. Fuel complexes were dominated by litter, shrubs or non-woody understorey (e.g. grass) types. Extensive destructive and non-destructive sampling to quantify the fuels was undertaken along transects in each experimental plot. Four strata of fine fuel layers were defined: shrubs, herbs and ferns, surface litter and upper duff. Experimental plots were square, 10-15 m wide, and defined by 0.3 to 1.2 wide control strips assisted by a hose line during burning.

Wind speed was measured continuous at 1.7 m above ground approximately 10 m from each experimental plot. Three composite fuel moisture samples (one litter, one duff and one live) were sampled at random locations prior to ignition.

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<sup>5</sup>It should be noted that the authors dried their fuels at 80°C for 24 hours which is much less than the generally accepted 104°C for 24 hours (e.g. Cheney et al. (1993)), perhaps resulting in lower than actual FMC values—see discussion on Measurement issues.

94 experimental fires for fire behaviour studies were conducted when slope and wind direction were aligned within  $20^\circ$ . Line ignition occurred 2 m from the windward edge to allow both forward and backing spread observations. Fire behaviour measurements used 1.5-m-high poles located at regular distances along the plot axis as reference points. ROS was determined by recording the time at which the base of the fire front reached each pole. Flame height and flame angle were estimated visually and used to calculate flame length. Wind speed ranged from  $0.3 - 6.4 \text{ m s}^{-1}$ , surface dead FMC ranged  $8 - 56\%$ , air temperature  $2 - 22^\circ\text{C}$  and relative humidity  $26 - 96\%$ . ROS ranged  $0.004 - 0.231 \text{ m s}^{-1}$ .

Fernandes et al. (2002) found that three existing models underestimated ROS with significant differences between predicted and observed values, as much as 8-fold in one case. Undertaken non-linear least=squares analysis, they found that slope and wind speed were the most significant variables with dead FMC in a less significant role. A power law function with wind speed only (exponent 0.803) explained 45% of the variation in ROS. If wind speeds less than  $0.83 \text{ m s}^{-1}$  were excluded, the correlation coefficient increased to 0.996. Slope alone explained 30% of the variation. The final model selected for litter-shrub fuels (the general case for maritime pine stands) involved wind speed (power law, exponent 0.868) dead surface FMC (exponential, coefficient -0.035), slope and understorey fuel height. Fuel height was selected as could be considered a surrogate for the overall fuel complex structure effect on ROS. The model was then adapted through changes in constants to predict ROS in litter and non-woody understorey complexes. No assessment of the performance of this model was reported.

## Maquis (2003)

Bilgili and Saglam (2003) conducted a series of 25 field experiments in open, level shrubland of maquis fuel in southwestern Turkey. Average height of the fuel was 0.53 m and fires were conducted under a range of wind and fuel conditions. Each fire plot was 20 m wide by 30 m long. A meteorological station recorded air temperature, relative humidity, wind speed and precipitation at 1.8 m daily. Fuel characteristics were measured from random destructive sampling prior to the experiment series. Live and dead FMC was sampled immediately prior to ignition. During each fire, wind speed, temperature and relative humidity at 1.8 m were recorded at 1 min intervals using the automatic meteorological station. These were averaged over the period of fire spread. Wind speed ranged  $0.02\text{-}0.25 \text{ m s}^{-1}$ , FMC  $15.3\text{-}27.7\%$ .

Fires were lit with a drip torch along the upwind (20 m long) edge to quickly establish a line fire and were allowed to propagate with the wind across the plot. ROS was measured by recording time of arrival at a series of predetermined locations and ranged  $0.01\text{-}0.15 \text{ m s}^{-1}$ . ROS was strongly correlated with wind speed; a linear function explained 71% of observed variation. FMC was found not to have any significant effect on ROS, attributed to the narrow range studied. The final model used a linear function of wind speed (coefficient 0.495) and total fuel load, with an  $R^2 = 0.845$ .

# Quasi-empirical models

Where the data gathered from experimental observation is analysed using a physical framework for the functional relationships between dependent and independent variables, a quasi-empirical model results. The degree to which the physical framework controls the structure of the model can vary but the nature of the model is essentially based upon the observed data (which differentiates it from quasi-physical models which use data solely for parameterisation). Table 2 summarises the quasi-empirical models discussed below.

## TRW (1991)

Wolff et al. (1991) presented the results of laboratory experiments conducted in a purpose-built wind tunnel 1.1 m wide by 7 m long with a moveable ceiling. The fuel layer was vertical match splints (1.3-4.4 mm in diameter) set in a ceramic substrate. Wind speed varied from 0-4.7 m s<sup>-1</sup>, ROS ranged from 0-0.007 m s<sup>-1</sup>. The results confirmed the theoretical treatment conducted by Carrier et al. (1991), in which it was hypothesised that the dominant heat transfer mechanism in such a set-up would be a mix of convection and diffusion (i.e. ‘confusion’) heating that would result in a relationship in which the ROS would vary as the square root of the wind speed normalised by the fuel load. If radiation was the predominant preheating mechanism, it was hypothesised that the variation would be as the power of 1.5 rather than 0.5.

Wolff *et al.* found that not only did the width of the fuel bed play an important part in determining the ROS but also the total width of the wind tunnel itself. The narrower the fuel bed, and the facility, the slower the ROS. It was suggested that a narrower fuel bed forced air away from the fuel bed due to drag considerations in the fuel. A series of experiments with tapering fuel beds and working section confirmed this. If the fuel bed and working section was too narrow, ROS ceased.

## NBRU (1993)

Beer (1993b, 1991) investigated the interaction of wind and fire spread utilising a series of 18 small-scale wind tunnel (length 40 cm, height 16 cm) experiments using a single row of match splints in wind ranging from 0.0 to 9 m s<sup>-1</sup>. ROS ranged from 0.004-0.38 m s<sup>-1</sup>. Rather than a single continuous function to describe the relationship between wind speed and ROS, Beer put forward the hypothesis that there exists a critical characteristic (threshold) wind speed that affects ROS with different wind speed functions above and below this value. Below the threshold Beer found a normalised (by the threshold wind speed) power function (exponent 0.5). Above the threshold, Beer found a normalised power function (exponent 3.0). Beer postulates that the choice of the value is related to the wind speed at which the wind shear is strong enough to generate flame billows and that this value corresponds to a mid-flame wind speed of 2.5 m s<sup>-1</sup>. Above this value it is thought that the flames remain within the fuel bed rather than above it. Beer attempted to fit this model to observations of grassfire behaviour but could not.

Beer (1993a) further explored the effects of wind on fire spread through simplified (match splints) fuel. His extension of a simple geometric model of fire spread in no wind to include

wind (based on geometry of wind-tilted flame and distance between fuel elements), in which the ROS-wind function is a complicated solution to a set of equations to determine the critical time for flame immersion of adjacent fuel elements, did not perform well. This was attributed to assumptions about the characteristics of the flame and a constant ignition temperature. Beer concludes that a single simple power law or exponential is unlikely to be a correct mathematical description for the ROS-wind speed relation.

## USFS (1998)

Catchpole et al. (1998b) conducted an extensive series of environmentally-controlled wind tunnel experiments and used the results, in conjunction with energy transfer considerations, to develop a spread model, USFS (United States Forest Service). 357 experimental fires were carried out on a fuel bed 8 m long by 1 m wide in a 12-m long wind tunnel of 3 m square cross section. Four fuels with different surface-area-to-volume ratios (two sizes of poplar excelsior, ponderosa pine needles and ponderosa pine sticks) were chosen to be reasonable approximations to natural fuel layers. Temperature and relative humidity were controlled to produce a range of FMC, 2% to 33% (although the majority of fires were carried out at ambient values of 27°C and 20% RH giving an FMC range of 5-9%). Wind speed above the tunnel's boundary layer ranged from 0.0 to 3.1 m s<sup>-1</sup>. Rate of spread was measured at 0.5 m intervals using photovoltaic diodes placed 25 mm above the fuel bed to record the time of arrival of the flame front.

Utilising the conservation of energy model of Fransden (1971), Fransden's (1973) effective heating number, a propagating flux model that is linear in packing ratio, and an exponential decay function for FMC, the authors built a model of fire spread very similar in its construction to that of Rothermel (1972) except that they used the heat of ignition of a unit mass of fuel (which comprises the heat of pyrolysis and heat of dessication) rather than the heat of pre-ignition as used by Rothermel. A power function for wind was then fitted to the data and an exponent of 0.91 determined. Although a cubic polynomial function was found to better fit the data, the authors chose the power function as it was more consistent with data from wildfire observations.

## Coimbra (2002)

Viegas (2002) presents a quasi-empirical model of fire spread that utilises the geometry of the fire perimeter to determine the forward spread rate. The main conceit of this notion, previously proposed in Viegas (1998) and Viegas et al. (1998), is that a line fire lit at an angle to a slope or wind gradient undergoes a translation and rotation of the fireline in order to spread with the maximum rate in the direction of the gradient. Extensive laboratory experimentation utilising a double-axis tiltable fuel bed (1.6 m × 1.6 m) for a range of forward/back and left/right slopes was used to develop the model. The fuel was *Pinus pinaster* needles with an FMC determined by ambient conditions (ranging 10% - 15%). 23 experimental fires were conducted, with 10 fires of varying slope and 13 fires of varying inclination. Viegas (2002) found a maximal rotation velocity at an inclination angle of 60° but was unable to convert this to a forward ROS. However, Viegas does develop a fire perimeter propagation algorithm in which the perimeter is treated as a continuous entity that will endeavor to align itself with the gradient, through



this proposed rotation mechanism, to an angle of approximately  $60^\circ$ . The translation and rotation hypothesis, however, ignores a basic observation of the evolution of flanking spread and instead assumes that spread at non-parallel angles to the slope or wind gradient must be driven by a headfire.

Viegas (2005) attempts to extend these ideas to describe the phenomenon of ‘fire blow-up’ based on the concepts of fire ‘feedback effects’. Viegas proposes the existence of a positive dynamic feedback between the ROS of a fire and the flow velocity driving the fire such that the fire accelerates exponentially. He uses some of the results of experimental fires burnt in a “canyon”, a doubly-sloped tray, in no wind and a range of canyon slopes and inclinations to parameterise his model and the remainder to test it. Viegas treats all data for all slope and inclination combinations as independent and continuous. As a result, his model increases ROS exponentially, resulting in extremely rapid acceleration—what he describes as blow-up. However, categorised by slope, rather than treated continuously, the ROS data actually asymptotes to a reasonable number in each case, which in most cases confirms the long-held rule of thumb of doubling the flat ground ROS for every 10 degrees increase in slope (McArthur, 1967; Van Wagner, 1988). Viegas (2006) conducts a parametric study of this model and determines that fires in light and porous fuels are more likely to exhibit ‘eruptive’ behaviour than fires in heavy and compacted fuels.

Viegas’s extrapolation of this model to fatal wildfire incidents is tenuous at best and really only proves the widely accepted acceleration up a slope. Other, more robust, theories of unexpected fire behaviour resulting in fatalities are probably more applicable (e.g. Cheney et al. (2001)).

## Nelson (2002)

Nelson (2002) extended the quasi-empirical work of Nelson and Adkins (1988) utilising the laboratory data of Weise and Biging (1997) to build a trigonometric model of fire spread that combines wind and slope effects into a single combined ‘effective’ wind speed.

The Nelson and Adkins (1988) model utilised the dimensional analysis of fire behaviour of Byram (1966), where three dimensionally homogeneous (i.e. dimensionless) relations were derived: 1) the square root of the Froude number, 2) a buoyancy number relating convective heat output to rate of buoyancy production, and 3) the ratio of combustion time to time characteristic of flame dynamics. Nelson and Adkins (1988) then used spread observations from 59 experimental fires (a total of 44 lab and 21 field, some deleted) and mixed and matched the dimensionless relations until they found a combination that gave a reasonable correlation. They derived a dimensionless form of ROS and wind speed, which, when fitted to the data and converted back to dimensions, gave a power law relation between wind speed and ROS (exponential 1.51). As the maximum wind speed used to obtain the data was  $3.66 \text{ m s}^{-1}$  and maximum observed ROS was  $0.271 \text{ m s}^{-1}$ , Nelson and Adkins (1988) acknowledged the need for higher wind speed experiments. ROS was also found to be a function of fuel load (power function, exponent 0.25) and residence time (inversely proportional). FMC was considered to be accounted for in the estimate of fuel load and residence time.

Rather than the traditional approach used by McAlpine et al. (1991) where the equivalent wind speed for a slope-only ROS was determined, Nelson (2002) used the concept of

vertical buoyant velocity and the slope angle component of this wind to construct a slope-induced wind which was then added vectorally to the ambient wind across slope. Nelson extended the dimensional analysis of Nelson and Adkins (1988) to then determine ROS. The resultant equations, which do not apply to flanking or backing fires due to the assumption about convective heating through the Froude number, were then compared against the data of Weise and Biging (1997), gathered from 65 experiments in a portable tilting wind tunnel using vertical paper birch sticks as the fuel bed in a variety of wind and slope configurations, ranging from 0.0 to 1.1 m s<sup>-1</sup> and -30° to +30°. The effective wind speed was found to correlate linearly with ROS.

## Discussion

### Wind speed function

As stated earlier, one method of comparing the structure of each of the above models is to examine the form of the functional relationship between ROS and wind speed chosen by the authors. Table 3 summarises the models discussed and the form of the wind speed function chosen. Also listed are the experimental bounds of the wind speed and ROS.

Only three of the models for which the wind function is given are not power functions, PortShrub and CFBP are exponential and Maquis is linear. Of the remaining models, 3 models have exponents less than one: TRW, CSIRO Grass and USFS. The remaining wind functions all result in non-linear increases (Figure 1) in the ROS that will result in a speed greater than the wind speed driving it, which is unphysical (Beer, 1991). (While this is also the case also for CFBP as illustrated here for wind speeds  $> 15$  m s<sup>-1</sup>, the ROS function is further modified in the CFFDRS system by fuel-specific functions which can reduce the predicted ROS below the wind speed.) The reason for this choice of function appears to be the desire by the modellers to fit data at low wind speeds (including zero). Many of the models had ranges of wind speed that were fairly low ( $< 3$  m s<sup>-1</sup>).

The few models that were based on large ranges of wind speed in field experiments (with the exception of CALM Jarrah II) tended to result in power functions with exponents less than one. CSIRO Grass is the highest power function less than one and is very similar in form to the linear function of Maquis over the given range. Fendell and Wolff (2001), in their brief review of the topic including a number of older models, found that the wind power function exponents ranged from 0.42 (Thomas, 1967) to 2.67 (Burrows, 1999b).

There seem to be two key factors in the choice of functional relationship used to describe fire spread and wind speed. The first is the need to fit the function through the origin. In many cases, particularly laboratory experiments, zero wind speed is taken as the default state and thus any continuous function must not only fit the data of non-zero wind, but also of zero wind. This is discussed in greater detail below. The second is that for the most part, the range of wind speeds studied (again particularly in the laboratory) is very small. As can be seen in Figure 1, any function, be it cubic or very shallowly linear, performs rather similarly at low wind speeds ( $< 1.5$  m s<sup>-1</sup>).

It is interesting to note that in the full range of functions presented here, the nearly median wind function in Figure 1 (i.e. Heath) is the result of the combination of multiple

datasets, experimental methods and authors, perhaps resulting in a middle ground of approaches. Many physical models of fire spread (e.g. Grishin (1984); Linn (1997)) have observed linear functional relationships between wind speed and ROS, suggesting that power law functions with exponents close to unity may have a more fundamental basis.

In their validation of the performance in Mediterranean shrub fuels of seven wildland fire spread models, including the CFBP and Rothermel, Sauvagnargues-Lesage et al. (2001) found that a model's performance is not related to the model's complexity and that even the most simple model (in this particular case a local fire officer's rule of thumb based on a linear discount of the wind speed) performed as well as more complicated models such as CFBP.

## Threshold wind speed

One important aspect differentiating the various choices of wind function, is the ideal of a continuous function that includes zero wind speed. It has been noted previously (Burrows et al., 1991) that fires in discontinuous fuels such as spinifex have a minimum wind speed required before forward spread is achieved. This notion was extended further by Cheney et al. (1998) to define a threshold wind speed at which fires spread forward *consistently*. The argument is that fires burning in low winds in the open respond to eddy fluctuations in the wind flow (resulting in near circular perimeter spread after a long period) and do not spread in a continuous consistent manner until the wind speed exceeds a certain threshold. Above this threshold, the fire spreads forward in a manner directly related to the wind speed.

The choice of threshold value is dependent then upon the method of measuring the wind speed (location, height, period, etc) and the fuel type in which the fire is burning (taller fuels reduce the wind speed reaching the fire). Cheney et al. (1998) chose a  $1.39 \text{ m s}^{-1}$  open wind speed threshold for open grasslands. Fernandes et al. (2002) found that wind speed explained more variation in ROS when wind speeds below  $0.83 \text{ m s}^{-1}$  (at 1.7 m) were excluded, suggesting that at low wind speeds factors other than wind play a more significant role in determining ROS.

## Fuel moisture content function

Another method of comparing the various empirical and quasi-empirical models is that of fuel moisture content function. Not all the models discussed here addressed the relation between fuel moisture content and rate of spread, and so the discussion here is not comprehensive. Figure 2 shows the various functions for those models that include fuel moisture content.

As with the wind function, there is a wide spread of functional forms used to described the influence of FMC on ROS, perhaps reflecting modelling approaches, methods or personal choice. There appear to be three types of functions representing the fuel moisture content/ROS function: weakly linear (e.g. Gorse (normalised) or CALM Spinifex (normalised)) in which the FMC plays a minor role in determining the ROS, strongly exponential (e.g. CALM Jarrah II and USFS) in which FMC plays a strong role until very low

FMC values, and strongly linear or weakly exponential (which might be approximated to linear) in which the role of FMC is spread over a large range of values. The majority of models discussed here fall into the latter group.

The weakest of the linear models (Gorse (normalised)) is characterised by few experiments with a limited range of FMC values, which raises the issue of how many sample points are needed to properly inform functional choice and model validation—one could argue that 9 fires is simply not enough given the range of the uncontrolled variables.

The weakly exponential group of models, which includes strictly linear models (e.g. CALM-Spinifex), appears to be the most robust in terms of range of FMC values and experimentation. It is interesting to note the similarity between the CALM Mallee and the CSIRO Grass models. The large difference in functionality between the strongly exponential and weakly exponential is interesting and may reflect differences in functionality as a result of wind function modelling, as all modelling identified wind speed as the primary variable and FMC as the secondary.

## Measurement issues

All empirical science is limited by the ability to measure necessary quantities, to quantify the errors in those measurements, and then relate those measurements to the phenomenon under investigation and wildland fire science is no different. Sullivan and Knight (2001) discussed the determination of the errors in measuring wind speed under a forest canopy some distance from an experimental fire and relating that measurement to measurements of fire spread. The issues of where to measure (location, height, in the open, under the canopy, etc.), how long to measure (instantaneous, period sampling, average, period of average, etc.), and how to correlate measurements with observations are complex and necessarily require approximations and simplification in order to be undertaken.

Similarly, destructive sample of FMC has issues that complicate a seemingly simple quantity. The time of sampling (morning, afternoon, wetting period, drying period), the general location (in the open or under the canopy, in the sun, in the shade, in between, etc.), the specific location (surface litter fuels, profile litter fuels, mid-layer fuels), the species of fuel (predominant fuels, non-predominant fuel, live, dead, etc.). Also once the samples have been taken there then is the issue of best drying methods for the particular samples to ensure a water-free weight, the best method of determining an average value for a plot, variance, error, etc.

Quantifying other factors such as fuel, again seemingly simple quantities rely upon a knowledge of the mode of combustion of the fire and which aspects of the fuel most influence that combustion and therefore the behaviour of the fire. These include definition of fuel strata (which itself depends on the intensity of the fire and which parts of the fuel complex will be burning during the fire and thus contribute to the energy released by the fire), the structure of the fuel and the size of fuel particles important to fire behaviour of the front, flanks and behind the flame zone, the amount of fuel available, the amount consumed, the chronology of the consumption of the fuel, the mode of consumption, transport of burning fuel (i.e. firebrands), spatial and temporal variation of these fuel and fire characteristics, determination of averages and methods of averaging, determination of errors, etc. The list could continue. Other factors, such as air temperature and relative

humidity, insolation, atmospheric stability, slope, soil type and moisture, have their own range of measurement difficulties, and are by no means the only quantities involved in quantifying the behaviour of wildland fires.

Laboratory-based experiments may aim to reduce the variation and control the errors in measurement of many of these quantities but are not immune to the difficulties of measurement.

## Field versus laboratory experimentation

Empirical or quasi-empirical modelling of fire behaviour has resulted in significant advances in the state of wildfire science and produced effective operational guides for determining the likely behaviour of wildfires for suppression planning purposes. Unlike physical or quasi-physical models of fire behaviour, these systems are simple, utilise readily available fuel and weather input data, and can be calculated rapidly. However, there is a significant difference between those models developed from field experimentation and those developed from laboratory experimentation.

Large-scale field experiments are costly, difficult to organise, and inherently have many of the difficulties associated with wildfire observations (e.g. spatial and temporal variation of environmental variables, uncontrolled variations, changing frames of reference and boundary conditions, etc.). Laboratory experiments can be cheap and safe, provide relatively repeatable conditions, and can limit the type and range of variations within variables and thus simplify analysis. Van Wagner (1971) raises the issue of laboratory versus field experimentation but avoids any categorical conclusions (perhaps because there are none), simply stating some features of wildland fire behaviour are better suited to studying in the controlled environment of the laboratory or could not be attempted in the field, and other features cannot be suitably replicated anywhere but in large-scale outdoor experiments.

Correct scaling of laboratory experiments (and field experiments for that matter) is vital to replicating the conditions expected during a wildfire. Byram (1966) and Williams (1969) conducted dimensional analysis of (stationary) mass fires in order to develop scaling laws to conduct scaled model experiments. Both found that scaling across all variables presents considerable difficulty and necessitates approximations, particularly in regard to atmospheric variables, which result in impractical lower limits (e.g. model forest fires  $\simeq$  6-16 m across (Byram, 1966), or gravitational acceleration  $\simeq$  10 g (Williams, 1969)). As a result, it is clear that any scaled experiments must take great care in drawing conclusions that are expected to be applicable at scales different from that of the experiments; not only may physical and chemical processes behave differently at different scales but the phenomena as a whole may behave differently.

The key difference between field-based and laboratory-based experimentation, in this author's opinion, is the assumptions about the nature of combustion (including heat transfer) that are required in order to design a useful small-scale laboratory experiment. That is, there is the presumption implicit in any laboratory experiment that there is sufficient understanding about the nature of fire such that key variables can be isolated and measured without regard to the fire itself.

One such aspect identified by Cheney et al. (1993) is the importance of the size and shape of the fire in determining resultant fire behaviour. Prior to this work, it was thought that

the size of the fire played little part in determining the behaviour of a fire and thus the results of small experimental fires could be extrapolated to larger fires burning under less mild conditions. Other factors such as the physical structure of the fuel or moisture content of live fuels, or other hitherto unconsidered factors, may play less significant but important roles in explaining the unaccounted variation in ROS.

Field experiments on the other hand, by their very nature, are real fires and thus incorporate all the interactions that define wildland fire. This aspect holds considerable weight with end users who endow such systems with a confidence that purely theoretical or laboratory-only-based models do not receive. As Morvan et al. (2004) concluded, no single approach to studying the behaviour of wildland fire will provide a complete solution and thus it is important that researchers maintain open and broad paradigm

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Table 1: Summary of empirical models discussed in this paper

Model	Author	Year	Country	Field/Lab	Fuel type	No. fires	Size (w × l) (m) <sup>6</sup>
CFS-accel	McAlpine	1991	Canada	Lab	needles/Excel.	29	0.915 × 6.15
CALM-Spin	Burrows	1991	Aust.	Field	Spinifex	41	200 × 200
CFBP	FCFDG	1992	Canada	Field	Forest	493	10-100 × 10-100
Button	Marsden-Smedley	1995	Aust.	Field	Buttongrass	64	50-100 × 50-100
CALM Mallee	McCaw	1997	Aust.	Field	Mallee/Heath	18	200 × 200
CSIRO Grass	Cheney	1998	Aust.	Field	Grass	121	100-200 × 100-300
Heath	Catchpole	1998	Aust.	Field	heath/shrub	133	100
PortShrub	Fernandes	2001	Portugal	Field	Heath/shrub	29	10
CALM Jarrah I	Burrows	1999	Aust.	Lab	Litter	144	2.0 × 4.0
CALM Jarrah II	Burrows	1999	Aust.	Field	Forest	56	100
PortPinas	Fernandes	2002	Portugal	Field	Forest	94	10-15
Gorse	Baeza	2002	Spain	Field	gorse	9	33
Maquis	Bilgili	2003	Turkey	Field	maquis	25	20
CSIRO Forest	Gould	2006	Aust.	Field	Forest	99	200 × 200

Table 2: Summary of quasi-empirical models discussed in this paper

Model	Author	Year	Country	Field/Lab	Fuel type	No. fires	Size (w × l) (m)
TRW	Wolff	1991	USA	Lab	match splints	?	1.1 × 7
NBRU	Beer	1993	Aust.	Lab	match splints	18	0.4 × 0.16 (2D)
USFS	Catchpole	1998	USA	Lab.	Pond./Excel	357	1.0 × 8.0
Coimbra	Viegas	2002	Spain	Lab	Pond. needles	23	3.0 × 3.0
Nelson	Nelson	2002	USA	Lab.	Birch sticks	65	?

<sup>6</sup>Where only one dimension is given by the authors, this is assumed to be both width and length of the fire or plot

Table 3: Summary of empirical models discussed in this paper

Model	Field/Lab	Fuel type	FMC Fn	FMC Range (%)	Wind Fn	Wind Range (m s <sup>-1</sup> )	ROS Range (m s <sup>-1</sup> )
<i>Empirical</i>							
CFS-accel	Lab.	Pond./Excel	-	-	-	0-2.22*	?-?
CALM-Spinifex	Field	Spinifex	$-82.08M$	12-31	$U^2$	1.1-10	0-1.5
CFBP	Field	Forest	$e^{-0.1386M}(1 + M^{5.31})$	?	$e^{0.05039U}$	?	?
PWS-Tas	Field	Buttongrass	$e^{-0.0243M}$	8.2-96	$U^{1.312}$	0.2-10	?-?
CALM Mallee	Field	Mallee	$e^{-0.11M_{ld}}$	4-32	$U^{1.05}$	1.5-6.9	0.13-6.8
CSIRO Grass	Field	Grass	$e^{-0.108M}$	2.7-12.1	$U^{0.844}$	2.9-7.1	0.29-2.07
Heath	Field	heath/shrub	NA	NA	$U^{1.21}$	0.11-10.1	0.01-1.00
PortShrub	Field	Heath/shrub	$e^{-0.067M}$	10-40	$e^{0.092U}$	0.28-7.5	0.01-0.33
CALM Jarrah I	Lab.	Litter	$\frac{1}{0.003+0.000922M}$	3-14	$U^{2.22}$	0.0-2.1	0.002-0.075
CALM Jarrah II	Field	Forest	$23.192M^{-1.495}$	3-18.6	$U^{2.674}$	0.72-3.33	0.003-0.28
PortPinas	Field	Forest	$e^{-0.035M}$	8-56	$U^{0.868}$	0.3-6.4	0.004-0.231
Gorse	Field	gorse	-0.0004M	22-85	NA	< 1.4	0.004-0.039
Maquis	Field	maquis	NA	15.3-27.7	$0.495U$	0.02-0.25	0.01-0.15
TRW	Lab.	match splints	NA	NA	$U^{0.5}$	0-4.7	0-0.007
NBRU	Lab.	match splints	NA	NA	$U^3$	0-9	0.004-0.38
USFS	Lab.	Pond./Excel	$\frac{\exp^{-4.05M}}{(700+2260M)}$	2-33	$U^{0.91}$	0-3.1	0-0.23
Coimbra	Lab.	Pond. needles	NA	10-15	-	?	?
Nelson	Lab./Field	Birch sticks	NA	NA	$U^{1.51}$	0.0-3.66	< 0.271

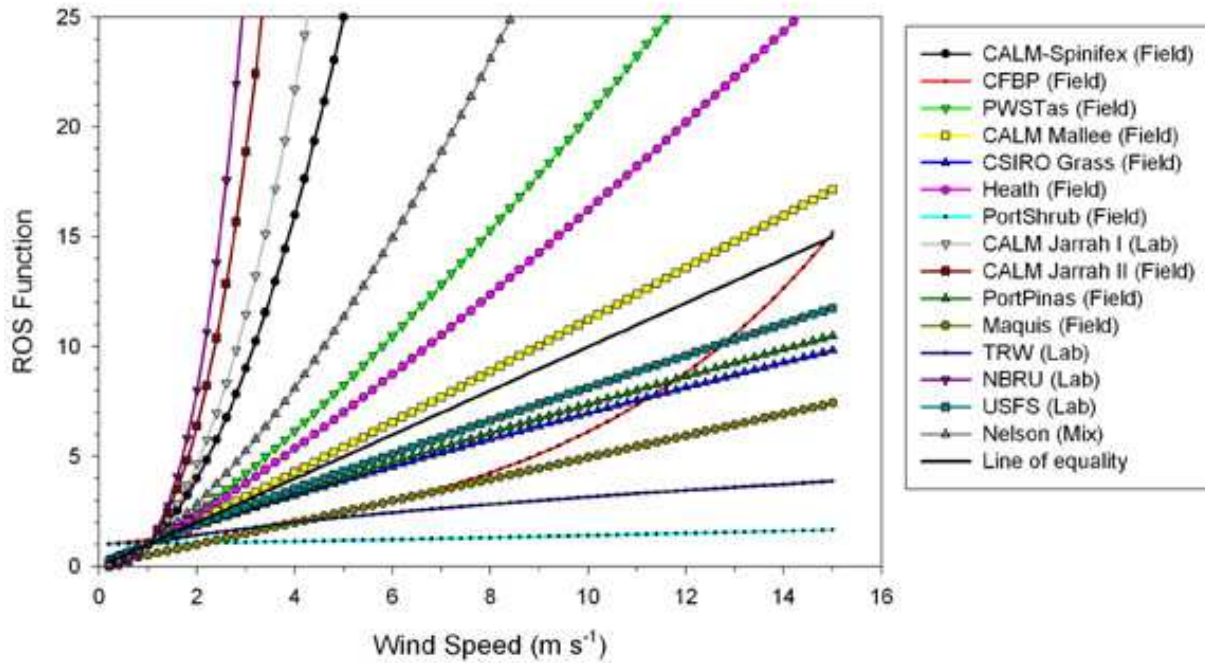


Figure 1: Graph of functional relationships between wind speed and rate of forward spread used in various empirical and quasi-empirical fire spread models. The relationship is only indicative of effect on ROS as the full model in each case may also include effects of other variables such as fuel moisture content as well as increases or decreases in wind speed due to measurement at different heights.

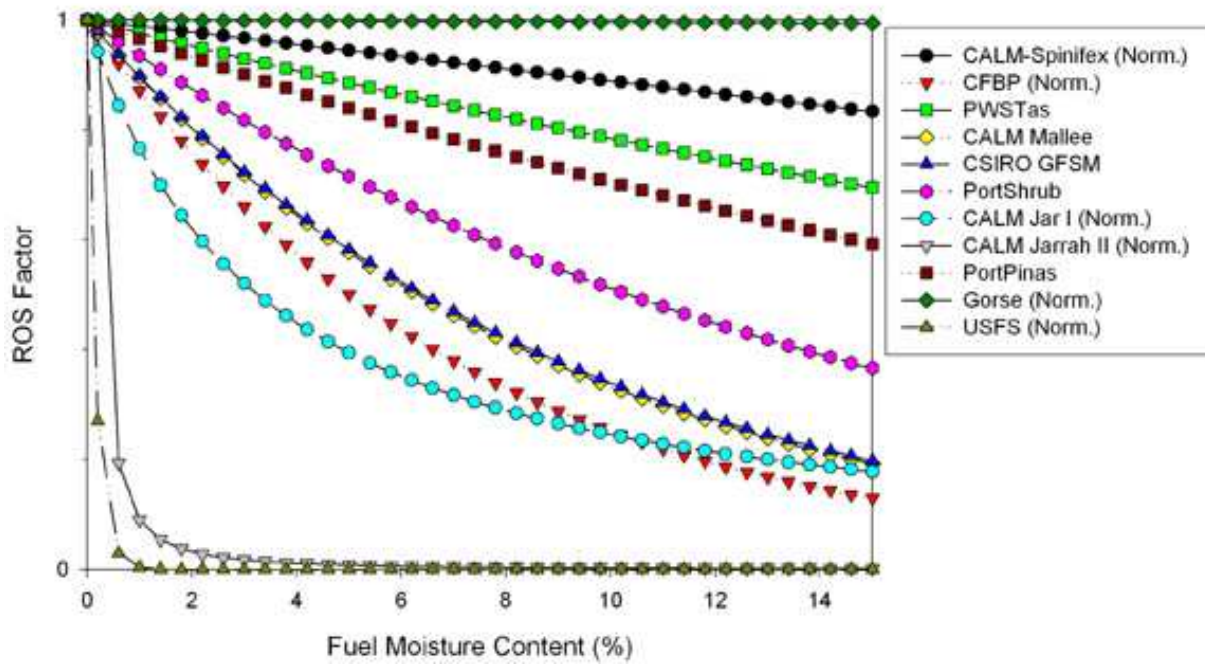


Figure 2: Graph of functional relationships between fuel moisture content and a rate of forward spread factor used in various empirical and quasi-empirical fire spread models. A number of models have been normalised in order to present them in conjunction with other models (i.e. norm.) The ROS factor shows the effect fuel moisture content has on the final rate of spread value in each model.